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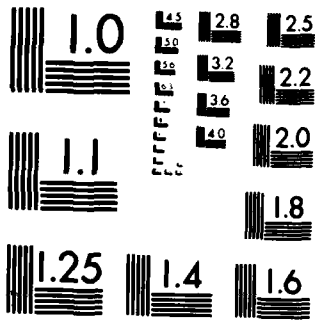
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A SYSTEMATIC STUDY OF LIGHT SCATTERING BY IRREGULARLY SHAPED PARTICLES

AD-A150 192

FINAL REPORT

RU T. WANG

NOVEMBER 26, 1984

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ABSTRACT

This final report summarizes the research activities under the ARO contract DAAG29-81-K0104 during the period May 29, 1981 through August 28, 1984, a productive period of our continuing 'Systematic Study of Light Scattering by Irregularly Shaped Particles.' Toward the end of the first fiscal year, Dr. D.W. Schuerman, the Principal Investigator, was tragically killed in an automobile accident (May 19, 1982). After consultation with ARO, Dr. R.T. Wang was named acting PI. The restructured scattering "group" now includes Dr. B.A.S. Gustafson and Dr. S.S. Hong, the last being a theoretician with extensive experience in scattering problems applied to astrophysics. Administrative guidance was provided by Dr. J.L. Weinberg, Space Astronomy Laboratory Director, and by Dr. F. Giovane, the Associate Director for Engineering.

The beginning one and one-half years were devoted to the analysis of existing experimental data and the related theoretical light-scattering studies, in parallel with the reconstruction, renovation and calibration of the microwave analog scattering facility then relocated from the Albany, N.Y. area. Extensive engineering assistance was provided by H.M. Mann, J. McKisson and R.C. Hahn, the last being our project engineer prior to relocation. The following one and one-half year period was devoted to actual measurement tasks and analysis of data in our original proposal; e.g., the investigations of scattering by interacting spheres and by particles with rough surfaces. Simultaneous with these measurements a number of 2:1 finite cylinders were also measured on their extinction properties when they were either preferentially or randomly oriented in space.

Our former semi-annual ARO progress reports described these step-by-step research achievements in some detail, but we also summarize here the important findings, along with a brief description of the new relocated-to-Gainesville facility. In doing so, it is best discussed by frequent references made with respect to the publications/reports of this period listed at the end of this final report.

BRIEF DESCRIPTION OF THE MICROWAVE SCATTERING FACILITY (MSF)

Our current MSF is housed in a large metallic building and occupies an indoor space 24 m x 12 m x 7 m (height). The anechoic chamber designs, layouts of microwave gears, antennas, compensation waveguide circuitries, particle-hoist and -orientation mechanisms, computer-controls of particle orientations and data loggings, etc. are the outgrowth of our past 20 years of experience in the Albany-Troy, N.Y. area [See also publication list 1,6, 13,14,15,16]. The success of employing the microwave analog measurement technique hinges most importantly on its unique capabilities of (1) precisely controlling the basic scattering parameters such as particle size, shape, index of refraction and orientation with respect to the incident beam; and (2) discriminantly measuring the desired true scattered wave against the unwanted coherent background wave via the compensation technique, even in the beam direction. Of these two, the second in turn depends heavily on the availability of a highly coherent microwave source (well stabilized in frequency). For this reason, we have continuously employed such a source since the inception of MSF in the late 1950's, even though it has to be overhauled frequently and is no longer suited to our needs. Shortly before the end of the reporting period, we were awarded a DoD-URIP grant to upgrade the MSF, and improvement of the measurement system is well under way. In addition to the careful selection of a new programmable microwave source of high frequency stability, better signal-conditioning electronics, low-noise GaAs microwave amplifiers, versatile minicomputer and peripherals for controlling data loggings, etc. are to replace the old MSF employed in this reporting period; the ultimate goal being to have a capability for measuring pertinent Mueller

Scattering Matrix elements in the upgraded MSF. An air-conditioned control room houses the computer facility for the scattering measurements and a special-purpose room was recently added to the facility to house the signal sources and our microwave refractive-index measurement system.

The operational procedures of the MSF have been reported elsewhere [e.g., see 13,14,15,16]. Four distinct types of measurement can be made using the MSF. They are: (1) Complex dielectric constant determination for scattering samples by observing the standing wave patterns in a waveguide-slotted-line device. The same device can be employed to measure or match the microwave impedances of various components of MSF. (2) Extinction by arbitrarily oriented particles. This set up allows simultaneous display of the $\theta = 0$ scattering amplitude and phase. (3) Angular distribution of scattering by arbitrarily oriented particles. A receiver antenna mounted on a mobile cart allows the detection of the scattered wave, polarized in arbitrary direction, in the continuous angular range $0 < \theta < 172^\circ$. (4) Backscattering ($\theta = 180^\circ$) by arbitrarily oriented particles. Of these 4, the first can be performed independently of the others while (2) and (3) are presently done in separate steps. (4) requires a modification in the microwave circuitries of (2) and (3) and was not done during this period. In all cases (2) - (4), the microwave-unique compensation technique is advantageously employed to accurately measure the true scattered wave: i.e., in the absence of a scatterer, one cancels the background radiation at the output port of a mixer hybrid by properly manipulating the amplitude and phase of a reference wave which is separately piped from the signal source to one of the two mixer input ports. As the scatterer is hoisted into the beam, the off-balance appearing in the same output port is the desired scattered wave, which is detected and displayed.

RESEARCH FINDINGS

A. Analysis of MSF Data Prior to Relocation and Related Theoretical Work

Simultaneous to the selection of the new laboratory site, remodelling of the interior, construction of the anechoic chamber and other activities associated with the establishment of the Gainesville MSF, which lasted until November 1982, intense analysis and theoretical works related to organizing the earlier MSF data were continued. Major research findings from this activity are:

- (1) On Dependent Scattering by Multiple Spheres. This is the analysis of multiple-sphere scattering data compiled under Army contract DAAG29-79-C-0055 [See the publication list 1,2 and 3]. A number of 2-, 4-, and 8-sphere arrays were investigated as to their scattering properties, with emphasis placed on extinction studies. (a) Interaction between two neighboring spheres is the strongest when the 2-sphere array axis is aligned in the beam direction, where the total cross section may vary as much as a factor of seven with sphere separation. (b) Weakest interaction between two neighboring spheres occurs when the array axis is perpendicular to the incident beam. In this case the total cross section of a 2-sphere array is close to the simple sum of the individual sphere's extinction cross sections. (c) Striking resonance can be observed at scattering angles near 90° , where two identical neighboring spheres may enhance the scattering intensity as much as 50 times that of the individual intensity at certain aspect angles, while almost nulling the intensity at other angles.

- (2) On Obscuration of Light by Axisymmetric particles. This is the analysis of data compiled under Army Grant DAAK-11-81-M-0010 [See 5,7].

Extinction by randomly oriented axisymmetric particles (a total of 49 spheroids, cylinders and disks [6]) were analyzed, and the result was displayed in the graphical form of volumetric extinction efficiency

$$\overline{Q_{\text{ext},v}} = \overline{C_{\text{ext}}} / \pi a_v^2 \text{ versus volume-equivalent phase-shift parameter } \rho_v = 4\pi a_v (m'-1)/\lambda, \text{ where } a_v \text{ is the radius of sphere equal in volume to the nonsphere.}$$

This work led us to important findings that:

(a) Randomly oriented nonspherical particles do exhibit resonance extinction with respect to variation in ρ_v . (b) For moderately low refractive indexes ($m' < 1.6$), particle volume and aspect ratio are the two dominant parameters in an extinction process. For a fixed aspect ratio, the extinction curve for randomly oriented nonspherical particles is therefore best plotted in $\overline{Q_{\text{ext},v}}$ versus ρ_v , whereby the salient physics of obscuration can be more easily seen.

- (3) The above findings motivated us to do a closer theoretical study on the Eikonal approximation for extinction processes and to explore the similarities and differences between light-wave and scalar-wave extinctions [8]. The application of the Eikonal approximation led to additional surprising discoveries [9] that: (a) it could qualitatively agree with the exact theory result for spheroids in predicting the extinction profiles; (b) it could also approximate the observed data on extinction, and, (c) randomly oriented flattened particles were more efficient volumetric obscurants than the similarly sized elongated particles of the same aspect ratio, if the aspect ratio was greater than ~ 3 and the particle size was above the first resonance.

- (4) Scattering by Randomly Oriented Axisymmetric Particles. This is the analysis of data accumulated shortly before the relocation of the MSF. The particles are referred to as the '28 particles' consisting of four 2:1 prolate spheroids, four 2:1 oblate spheroids, four 4:1 cylinders, four 4:1 disks, four spheres, four 4:1 prolate spheroids and four 4:1 oblate spheroids; the first 16 particles were directly measured both on extinction and on angular distribution, while the last 12 used data derived from the exact theories of Mie and of Asano and Yamamoto. All 28 particles have the common refractive index $m=1.61-10.004i$ so as to focus the investigation on particle shape effects. The analysis results have been presented in a number of publications during this period [4,5,6,7,9,11]. The analysis effort is still continuing since many researchers have requested more detailed data to check with their complex theoretical codes. Succinctly stated, the most important findings are: (a) The MSF results for spheroids agreed in most cases with the exact theory results of Asano and Yamamoto [Appl. Opt. 14, 29(1975)] and Asano and Sato [Appl. Opt. 19, 962(1980)], and thus our absolute magnitude calibration of the cross-polarized intensity component still depends on these theories. (b) Extinction by these particles follows the trends cited in (2) and (3). (c) The angular distribution of scattered radiation from a randomly oriented nonsphere is much more smoothed out than from a similarly sized smooth sphere, and the backscatter intensity from the former is considerably reduced compared to the latter. (d) The effects of particle shape show up most conspicuously in the angular dependence of the degree of linear polarization.

(5) Angular Scattering by Birds'-Nest Type Aggregated Particles.

Gustafson has continued the analysis of data in his doctoral thesis [Reports from the Observatory of Lund, Sweden #17 (1980), See also 10,12]. For some aggregated particles, such as an agglomerate of 125 small ($ka=0.47$) 4:1 randomly oriented cylinders held together by a styrofoam matrix, the observed angular distribution could be well approximated by adding the interfering wavelets scattered from individual cylinders, taking into account the phases of individual wavelets. Only four dominant parameters were thereby needed for the quantitative description.

B. New Gainesville MSF Data and Their Preliminary Analysis

Immediately following re-establishment of the new microwave scattering facility in November 1982, a series of new measurements was carried out over the next 20 months, interrupted intermittently only by failures/malfunctions of aging equipment, facility alignment/maintenance and other mandatory procedures. The new measurements are mostly for the completion of the tasks in our original proposal: the continued investigation of dependent scattering by multiple spheres and the study of effects of particle surface roughness. However, a series of extinction measurements were conducted on finite cylinders at the beginning for test runs and for the study of edge effects. Summary of the findings:

- (1) On Extinction by Finite Cylinders. This work is still in the process of analysis and will be reported in the near future. The preliminary findings are: (a) Extinction is very orientation sensitive for particles with aspect ratio greater than 2:1. (b) Effects of sharp edge appear to increase the

total absorption but reduce the total scattering (the net extinction being reduced), as compared to a similarly sized spheroid of the same aspect ratio and refractive index. This statement applies only to the case when the cylinder is randomly oriented.

- (2) On Scattering by Dumbbells and Chains of Spheres. This work has been reported in [13,14]. This is the continuation of the studies reported in [1,2,3]. The choice of dumbbell and linear chain for the array shape made the evaluation of scattering quantities averaged over random orientations possible, and the highly interesting findings were: (a) Extinction properties cited in A-(1) still hold, in agreement with our old data; i.e., the individual particles in an array obscure the incident beam independently of others when the array axis is perpendicular to the beam direction, while strongly interfering with each other when the axis is lined up in the beam direction. In the latter case, the extinction by the total array may become comparable to or even smaller than that of a single component sphere! (b) Randomly oriented arrays exhibit resonance extinction with respect to the variation in size, whereby the total volume and the aspect ratio of the array are the dominant parameters controlling the extinction profile. (c) Most startling discovery is in the results of angular scattering measurements [14], where we found the preservation of individual sphere's scattering signatures at high scattering angles, $\theta > 90^\circ$; i.e., the angular scattering intensity of an array was nearly equal to the sum of those of individual spheres, and the polarization by the array was closely approximated by that of a single component sphere! This statement applies only when the array is randomly oriented.
- (3) On Scattering by Rough Particles. Extinction and angular scattering by preferentially and randomly oriented rough particles were measured and

the data analyzed, and the results have been submitted to the 1984 CRDC Proceedings [15,16]. A total of 10 roughened-sphere-like particles of two shapes and two refractive indexes were investigated as to the effects of surface roughness on scattering. These 10 particles ranged in size from $\rho_v \approx 2$ to $\rho_v \approx 10.5$, where the volume-equivalent phase-shift parameter ρ_v is related to the radius of the equal-volume sphere, a_v , and the real part of refractive index, m' , by $\rho_v = 4\pi a_v (m' - 1)/\lambda$. This is the first detailed systematic measurement on scattering by resonance-sized rough particles and has provided rather exciting information, among them: (a) Unless the overall particle shape is not much different from a smooth sphere, a randomly oriented rough particle obscures the incident light nearly the same as a smooth sphere of equal volume and refractive index, even though the effect of surface roughness appears to increase the total absorption but reduce the total scattering. (b) The particle-orientation dependence of extinction increases as the particle size/surface roughness grows in size. (c) The angular distribution of scattering by randomly oriented rough particles has marked differences from smooth spheres depending on the particle size and on 3 distinct angular ranges: the forward scatter range, the middle angular range and backscatter angles. When $\rho_v < 5.5$ the scattering patterns in the first two regions are rather well predicted by Mie theory for equal-volume spheres, or, better still, by Mie theory for size-distributed spheres with a narrow gamma distribution around ρ_v of the particle. As ρ_v increases, the differences from the above theoretical results becomes larger, notably in the middle scattering angle range, where the Mie theory results underestimate the scattering intensities. Also, the forward scattering lobe of a large rough particle is noticeably narrower than the equivalent-volume sphere Mie

theory results. For all particle sizes the backscatter intensity by rough particles is reduced compared to the corresponding smooth spheres.

(d) The angular scattering from a rough particle is extremely particle-orientation sensitive, especially at high scattering angles, $\theta > 70^\circ$.

At a fixed θ , a factor ~ 1000 of intensity variation was observed frequently during a series of particle rotations. This corresponds to the 'twinkling' phenomenon manifested by a micron or sub-micron sized, rotating irregular particle as would be seen in a laser-based experiment.

LIST OF PUBLICATIONS/REPORTS

May 29, 1981 - August 28, 1984

1. Schuerman, D.W. and Wang, R.T., Experimental results of multiple scattering, CSL Contractor Rept. ARCSL-CR-81003, Army CSL, Aberdeen, MD (Nov. 1981).
2. Wang, R.T., Greenberg, J.M. and Schuerman, D.W., Experimental results of dependent light scattering by two spheres, Opt. Lett. 6 pp 543-545 (1981).
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4. Schuerman, D.W., Gustafson, B.Å.S., Wang, R.T. and Schaefer, R.W., Micro-wave analog and theoretical light-scattering results for ensembles of identical disks, spheroids, and cylinders, in 'Proc., 1981 CSL Scientific Conference on Obscuration and Aerosol Research,' R. Kohl, ed. ARCSL-SP-82022, pp 39-46, Army CSL, Aberdeen, MD (1982).
5. Wang, R.T. and Schuerman, D.W., Extinction by randomly oriented, axisymmetric particles, in 'Proc., 1981 CSL Scientific Conference on Obscuration and Aerosol Research,' R. Kohl, ed., ARCSL-SP-82022, pp 47-58, Army CSL, Aberdeen, MD (1982).
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7. Wang, R.T. and Schuerman, D.W., Extinction by randomly oriented, axisymmetric particles, CSL Contractor Rept. ARCSL-CR-82016, Army CSL, Aberdeen, MD (June 1982).
8. Wang, R.T., Similarities and differences between light-wave and scalar-wave extinctions by spheres, in 'Proc., 1982 CSL Scientific Conference on Obscuration and Aerosol Research,' R. Kohl, ed., ARCSL-SP-83011, pp 187-200, Army CSL, Aberdeen, MD (1983).
9. Wang, R.T., Extinction signatures by randomly oriented, axisymmetric particles, in the same 'Proceedings' as above pp 223-242 (1983).
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11. Wang, R.T., Obscuration of light by randomly oriented nonspherical particles (abstract), Aerosol Sci. and Tech. 2 187, Elsevier, N.Y. (1983).

12. Gustafson, B.Å.S., Dependence of side scattering by an ensemble of 43 cylinders on their configuration (abstract), Aerosol Sci. and Tech. 2, 161, Elsevier, N.Y. (1983).
13. Wang, R.T., Extinction by dumbbells and chains of spheres, in 'Proc. 1983 CRDC Scientific Conference on Obscuration and Aerosol Research,' J. Farmer & R. Kohl, eds., RHK & A, Tullahoma, TN. pp 223-235 (For speaker's draft only. Formal proceedings in press).
14. Wang, R.T. and Gustafson, B.Å.S., Angular scattering and polarization by randomly oriented dumbbells and chains of spheres, in the same 'Proceedings' as above pp 237-247 (in press).
15. Wang, R.T., Extinction by rough particles, submitted to the 'Proc., 1984 CRDC Scientific Conference on Obscuration and Aerosol Research,' R. Kohl, ed., Army CRDC, Aberdeen, MD.
16. Wang, R.T., Angular scattering by rough particles, submitted to the same 'Proceedings,' as above.

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